

# Phys 476: Modern Electronics for Physicists

## Spring semester 2025

### Instructor

- **Name:** Prof. Keisuke Yoshihara
- **Email:** kyoshiha@hawaii.edu
- **Office Hours:** Available by appointment. Please send an email to schedule a meeting.

### Class Information

- **Classroom/Lab:** WAT415A
- **Class Hours:**
  - **Tuesday:** 1:30 PM – 4:50 PM [Lecture + Lab]
  - **Thursday:** 1:30 PM – 3:20 PM [Lecture]

### Course Format

This course combines lectures and laboratory work to provide a comprehensive understanding of electronics in physics experiments. In the first half of the course, lectures focus on basic digital circuit design, introducing fundamental concepts and theories, while labs offer hands-on FPGA programming where students implement designs on FPGA training boards. In the second half, students engage in project work that simulates applications in cutting-edge physics experiments, creating their own artificial intelligence (AI) and machine learning (ML) algorithms, and using High-Level Synthesis (HLS) tools to implement these ML/AI algorithms on FPGAs. Lecture notes will be available in shared folder online.

### Programming

- **Experience Required:**
  - No prior programming experience is required. But programming experience with Python or other languages is an advantage
- **Languages Used:**
  - **Verilog:** Primary language for the course.
  - **Python:** Used in some exercises.
- **Tools and Environments:**
  - **Xilinx Vivado and Vitis HLS:** FPGA development tool
  - **hls4ml:** Tool for implementing ML models on FPGAs
  - Python coding environments to be set up in advance, such as Google Colab, Jupyter Notebooks, or Spyder.
- **Operating Systems:**
  - **No preference.** Linux, Windows, or macOS. Vivado does not support macOS
- **AI Tools:**
  - Use of AI tools like **ChatGPT** is permitted for coding and assignments.
  - Recommended to set up a free ChatGPT account accessible via your web browser.

## Prerequisite

- It is recommended that students have taken PHYS475. PHYS476 is suitable for students who are interested in digital circuits, AI/ML, or who are motivated to start research in these related fields. A willingness to actively engage with hardware design and programming is essential. If you are uncertain about your preparedness for the course, please consult with the instructor directly.

## Textbook

- **Recommended Textbook:** Russell Merrick, *Getting Started with FPGAs, Digital circuit design, verilog, and vhdl for beginners*
- (optional electronics Bible) Horowitz and Hill: *The Art of Electronics*

## Course Goals

This course aims to equip physics students with essential programming skills necessary for developing digital circuits with ML/AI algorithms in physics experiments. The course covers digital circuit design with Verilog/VHDL hardware description language, usage of high-level synthesis tools, and the implementation of ML/AI models on FPGAs.

## Learning Outcomes

By the end of this course, students will be able to:

- **Programming Proficiency:**
  - Write and understand basic to Python and Verilog programming.
- **Machine Learning Fundamentals:**
  - Understand fundamental ML algorithms and implement them using libraries.
- **Digital circuit designs:**
  - Understand fundamental digital circuits
  - Design digital circuits
  - Simulation, synthesizing, and implementing designed circuit into FPGAs
- **Problem Solving:**
  - Apply programming skills to solve physics problems and propose solutions.
  - Train ML algorithms using real experimental data to optimize results.

## Homework

- **Assignment Schedule:** Assigned **Tuesday**, due the following **Tuesday** at **1:30 PM**.
- **Submission Policy:** No late homework will be accepted unless you have a doctor's note or a comparable excuse.
- **Format:** Each assignment requires a short report summarizing results.

## Grading

Grades will be based on a total score composed of:

- **[70%] Homework Assignments:**
  - Weekly or bi-weekly assignments. Each assignment requires a short report summarizing results, including graphics.

- **[30%] Final Project:**

- A physics project that involves applying ML algorithms to real physics experimental data to optimize experimental sensitivity. In the final week of the course, students will give an oral presentation to showcase their results.

**Participation:**

Although participation is not directly graded, **attendance and active participation in lab sessions are essential** for hands-on experience and successful completion of homework and the final project. Full engagement in these sessions is expected.

Week	Date	Lecture Topics	Lab Activities
1	Jan 14	Lecture 1: Course Introduction and Overview <ul style="list-style-type: none"> <li>• Course objectives, materials, and setup explanation</li> </ul> Lecture 6: Combinational Circuit Design (Part 1) <ul style="list-style-type: none"> <li>• Boolean algebra and basic logic gates</li> </ul> Lecture 7: Introduction to Verilog (Basic) <ul style="list-style-type: none"> <li>• Syntax, modules, and combinational logic implementation</li> </ul> Lecture 9-1: Vivado Basics (Hands-on) <ul style="list-style-type: none"> <li>• Vivado software overview</li> </ul>	Vivado Design Flow, Combinational Circuit
1	Jan 16	Lecture 3: Transistors <ul style="list-style-type: none"> <li>• MOSFETs, CMOS basics, and transistor-level logic</li> </ul> Lecture 9-2: Vivado Basics (Hands-on) <ul style="list-style-type: none"> <li>• Debugging and simulation of basic circuits</li> </ul>	Continued
2	Jan 21	Lecture 4: Basics of CMOS Technology <ul style="list-style-type: none"> <li>• Characteristics and power efficiency in CMOS circuits</li> </ul> Lecture 8: Combinational Circuit Design (Part 2) (Lecture + Hands-on) <ul style="list-style-type: none"> <li>• Multiplexers, decoders, encoder, Comparator, Adder</li> </ul>	Testbench design, Simulation
2	Jan 23	Lecture 5: Introduction to FPGA <ul style="list-style-type: none"> <li>• FPGA internal architecture and configurable blocks</li> </ul> Lecture 8: Combinational Circuit Design (Part 2) (Lecture + Hands-on) <ul style="list-style-type: none"> <li>• Multiplexers, decoders, encoder, Comparator, Adder</li> </ul>	Continued
3	Jan 28	Lecture 10: Combinational Circuits (Part 3) <ul style="list-style-type: none"> <li>• Adders, Subtractors, Complementer</li> </ul> Lecture 11: Vivado Simulation (Hands-on) <ul style="list-style-type: none"> <li>• Debugging and simulation of basic circuits</li> </ul>	
3	Jan 30	Lecture 12: (Lecture + Hands-on) Sequential Circuits Design (Part 1) <ul style="list-style-type: none"> <li>• Flip-Flops, Latches, Ripple Counter</li> </ul>	Sequential Circuit: RSFF, DFF, and TFF
4	Feb 4	Lecture 13: (Lecture + Hands-on) Sequential Circuits Design (Part 2) <ul style="list-style-type: none"> <li>• Flip-Flops, Shift Registers, Binary Counter</li> </ul> Lecture 14 (Hands-on): Sequential Circuit in Vivado <ul style="list-style-type: none"> <li>• Implementation of Binary Counter</li> </ul>	Sequential Circuit: binary counter, external clock usage
4	Feb 6	Lecture 2: Data Acquisition Techniques in HEP <ul style="list-style-type: none"> <li>• Overview of DAQ systems and experimental apparatus</li> </ul>	Continued

5	Feb 11	Lecture 15 (Lecture + Hands-on): Advanced Circuits • Decimal Counter, Timer, Chattering Effect, Asynchronous to syn	Vivado Simulation
5	Feb 13	Lecture 16 (Lecture + Hands-on): Memory and FIFO • Memory and FIFO	FIFO design
6	Feb 18	Lecture 17 (Lecture + Hands-on): Simplified Physics Models • Hierarchical Design, Serializer/PacketBuilder, Muon lifetime	Physics Model Design
6	Feb 20	Lecture 18 (Lecture + Hands-on): Finite State Machine • State Diagram, LED example, Serializer in simplified model	Serializer as FSM
7	Feb 25	Spare Week (Flexibility for adjustments or catch-up)	Design your own model
7	Feb 27	Spare Week (Flexibility for adjustments or catch-up)	Design your own model
8	Mar 4	Special Lecture (Part1)	Matt Andrew (TBD)
8	Mar 6	Special Lecture (Part2)	Chris Ketter (TBD)
9	Mar 11	Lecture 19: Basics of Machine Learning Models (1) - Basic Structure of Machine Learning Models	Basic Python ML Implementation
9	Mar 13	Lecture 20: Basics of Machine Learning Models (2) - Convolutional Neural Networks (CNN), Feedforward Neural Networks (FNN)	
10	Mar 18	Spring Break	
10	Mar 20	Spring Break	
11	Mar 25	Lecture 21: Introduction to hls4ml	hls4ml hands-on
11	Mar 27	Lecture 22: Optimization of AI/ML algorithm	Continued
12	Apr 1	Lecture 23: Applications in Physics Experiments • DNN track trigger at Belle II • Beam Abort System at SuperKEKB	
12	Apr 3	Project Task Explanation	Project Work
13	Apr 8	Project Work	Project Work
13	Apr 10	Project Work	Project Work
14	Apr 15	Project Work	Project Work
14	Apr 17	Special Lecture (Part3) -- Versal FPGA, AI Engine	Yun-Tsung Lai (KEK) (TBD)
15	Apr 22	Project Work	Project Work
15	Apr 24	Project Work	Project Work
16	Apr 29	Project Work	Project Work
16	May 1	Project Work	Project Work
17	May 6	Project Work	Project Work
17	May 8	Final Presentation	Final Presentation
18	May 13	OFF	OFF
18	May 15	OFF	OFF

<https://docs.google.com/spreadsheets/d/1Iri6ho83O6IL45iehqbECc-Jx5IXfWVZTIZE9Oafkxk/edit?usp=sharing>